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U.S. PATENT APPLICATION

for

TEMPERATURE SENSING DEVICE

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TEMPERATURE SENSING DEVICE

BACKGROUND

[0001] The present description relates generally to temperature sensing devices such as thermostats, etc. More specifically, the present description relates to temperature sensing devices configured to compensate for mounting surface temperature effects.

[0002] Climate control systems, such as heating, ventilating, and air conditioning (HVAC) systems, typically include one or more thermostats to monitor, for example, an ambient air temperature within a particular room or zone within a building to provide feedback as to whether the air temperature of the room needs to be adjusted to satisfy a predetermined set point. The thermostat is typically configured such that a temperature sensor is housed within an enclosure to sense the temperature of the air passing over, through, or in contact with the enclosure. The climate control system may then compare this air temperature to the predetermined set point to determine if the air temperature of the room needs to be adjusted to satisfy the predetermined setpoint.

[0003] For convenience, the thermostat may be mounted to a wall or other surface within the room or zone. However, when the thermostat is mounted to the surface of an outside wall or another location where the wall surface is significantly warmer or colder than the air temperature of the room or zone, there may be substantial differences between the air temperature measured by the thermostat and the actual ambient air temperature of the room or zone. Further, air flow through the thermostat may be minimal due to a low profile enclosure designed such that the thermostat is minimally noticeable and does not project undesirably from the wall or other mounting location. Under these conditions, the climate control system may perform inefficiently because the temperature measured by the thermostat may not be the ambient air temperature of the room, but rather a temperature somewhere between the air temperature of the room and the wall surface temperature. Thus there is need for

an improved temperature sensing device with the capability to compensate for mounting surface temperature effects.

SUMMARY

[0004] According to a first exemplary embodiment, a temperature sensing device includes a first temperature sensor configured for mounting to a structure at a first distance relative to the structure, and a second temperature sensor configured for mounting to the structure at a second distance relative to the structure. The temperature sensing device also includes a processor coupled to the first and second temperature sensors and configured to estimate a third temperature based on the first and second temperatures and the distance separating the first and second temperature sensors.

[0005] According to a second exemplary embodiment, a method of sensing temperatures in a room includes mounting a first temperature sensor to a structure in the room at a first distance relative to the structure, mounting a second temperature sensor to the structure at a second distance relative to the structure, measuring a first temperature with the first temperature sensor, measuring a second temperature with the second temperature sensor, and estimating a third temperature from the first and second temperatures.

[0006] According to a third exemplary embodiment, a temperature sensing device includes a housing, a first temperature sensor mounted within the housing and configured to sense a first temperature, and a second temperature sensor mounted within the housing and spaced apart from the first temperature sensor, and configured to sense a second temperature. The temperature sensing device also includes a processor coupled to the first temperature sensor and the second temperature sensor and configured to estimate a third temperature using the first temperature and the second temperature.

[0007] According to a fourth exemplary embodiment, a method includes measuring a first temperature using a first temperature sensor mounted within a housing, measuring a second temperature using a second temperature sensor mounted within the housing and spaced apart from the first temperature sensor, and estimating a third

temperature from the first temperature and the second temperature using a processor coupled to the first temperature sensor and the second temperature sensor.

[0008] According to a fifth exemplary embodiment, a temperature sensing device includes a housing, a first temperature sensing means mounted within the housing and configured to sense a first temperature, and a second temperature sensing means mounted within the housing and spaced apart from the first temperature sensing means, and configured to sense a second temperature. The temperature sensing device also includes means coupled to the first temperature sensor and the second temperature sensor for estimating a third temperature from the first temperature and the second temperature.

[0009] According to a sixth exemplary embodiment, a temperature sensing device includes a first temperature sensor configured to sense a first temperature and a second temperature sensor spaced apart from the first temperature sensor, and configured to sense a second temperature. The temperature sensing device also includes a processor coupled to the first temperature sensor and the second temperature sensor and configured to estimate a heat transfer rate associated with at least one of the first temperature and the second temperature; and determine an air temperature set point based on the heat transfer rate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 illustrates a temperature sensing device according to an exemplary embodiment.

[0011] FIG. 2A is a diagram which schematically illustrates the electrical components of temperature sensing device of FIG. 1 according to an exemplary embodiment.

[0012] FIG. 2B is a diagram which schematically illustrates the electrical components of the temperature sensing device of FIG. 1 according to another exemplary embodiment.

[0013] FIG. 3 illustrates a temperature sensing device mounted to an exterior wall of a building according to an exemplary embodiment.

DETAILED DESCRIPTION

[0014] FIG. 1 illustrates a temperature sensing device 100 according to one exemplary embodiment. In one embodiment, temperature sensing device 100 is a thermostat, such as a wall-mounted electronic thermostat configured for use with a climate control system to measure the air temperature of a room. In other embodiments, temperature sensing device 100 may be adapted for use with other systems or locations. Temperature sensing device 100 includes a housing 102, temperature sensors 104 and 106, and a processor 108. Temperature sensing device 100 may be generally used to sense a first temperature and a second temperature and to estimate a third temperature using the first temperature and the second temperature. More specifically, temperature sensing device 100 may be used to compensate for external temperature effects resulting from the location of temperature sensing device 100 by measuring a first temperature and a second temperature, and estimating the third temperature based on the first temperature and the second temperature.

[0015] Housing 102 is configured to provide a structure within which temperature sensors 104 and 106, and optionally processor 108, may be mounted and enclosed. In the illustrated embodiment, processor 108 is shown as being enclosed within housing 102. In another embodiment, processor 108 is located within another device or controller remotely located and/or external to housing 102. Housing 102 is made of a rigid material such as a plastic or metal or other material suitable to protect the internal components of housing 102. In one embodiment, portions of housing 102 may be made of a thermally conductive material such that at least one of the temperatures sensed by temperature sensors 104 and 106 may be sensed by conduction through housing 102. In another embodiment, housing 102 may include one or more openings or vents to facilitate the flow of air through temperature sensing device 100 once it has been mounted such that at least one of the temperatures sensed by temperature sensors 104 and 106 may be sensed by convection through housing 102.

[0016] Housing 102 is further configured to be mounted to a structure. In the illustrated embodiment, housing 102 is configured to be mounted to the surface of a structure of a building, such as a wall, floor, ceiling, column, or other structure, using

any suitable mounting hardware or other means of attachment. The structure to which temperature sensing device 100 is mounted may be, for example, an exterior wall or other structure for which the temperature of the surface to which temperature sensing device 100 is mounted is different from, for example, the air temperature of a room or other area which includes or is exposed to the structure and in which temperature sensing device 100 is mounted.

[0017] Housing 102 may be any suitable size or shape depending on the particular application. For example, in the illustrated embodiment, housing 102 is an essentially rectangular hollow protrusion with a low profile such that housing 102 does not significantly extend beyond the surface of a structure, such as a wall, to which it is mounted. In this embodiment, housing 102 is shaped such that it has a surface 110 and a surface 112 spaced apart from surface 110. In the illustrated embodiment, housing 102 is formed from a mounting base 116 and a mating cover 118 such that mounting base 116 includes surface 110 and mating cover 118 includes surface 112. In other embodiments, housing 102 may be formed from additional pieces, or may be a single piece.

[0018] Surface 110 is configured to be adjacent to a surface of a structure, such as a wall, to which housing 102 is mounted. Surface 112 is configured to be spaced apart from the surface of the structure and exposed to a temperature at a distance from the surface of the structure, such as the temperature of the air at a distance from the surface of a wall to which temperature sensing device 100 is mounted. Preferably, surface 112 is spaced apart from surface 110 such that the distance between surface 110 and surface 112 is maximized while maintaining an overall low profile for temperature sensing device 100. For example, the embodiment shown in FIG. 1 includes a protrusion 114 extending from mating cover 118 which is configured to maximize the spacing between surface 110 and surface 112 while maintaining an overall low profile of temperature sensing device 100. In other embodiments, protrusion 114 may be eliminated, such that mating cover 118 is substantially planar.

[0019] Temperature sensors 104 and 106 may be mounted within housing 102, and may be any suitable temperature sensor. For example, in one embodiment, temperature sensors 104 and 106 may be resistance thermal detectors (RTDs). In

another embodiment, temperature sensors 104 and 106 may be thermistors. In one embodiment temperature sensors 104 and 106 may be electrical or electronic devices that provide an analog output signal. In another embodiment, temperature sensors 104 and 106 may be electrical or electronic devices that provide a digital output signal.

[0020] Temperature sensors 104 and 106 are configured to sense temperatures at different locations within housing 102. For example, in the illustrated embodiment, temperature sensor 104 is mounted proximate to surface 110 and temperature sensor 106 is spaced apart from temperature sensor 104 and mounted proximate to surface 112. Preferably, the spacing between temperature sensors 104 and 106 is the maximum possible spacing that housing 102 will permit. For example, in the illustrated embodiment, housing may be approximately 35 millimeters between surface 100 and surface 112, with temperature sensor 104 mounted on the inside of a 2 millimeter thick base 116, and with temperature sensor 106 mounted on the inside of a 1 mm thick cover 118. Of course, in other embodiments, other spacings between temperature sensors 104 and 106 may be optimal.

[0021] Temperature sensor 104 may be configured to sense the temperature at or near the surface of a structure, such as a wall to which housing 102 is mounted, and to which mounting base 116 and surface 110 are adjacent. Temperature sensor 106 may be configured to sense the temperature of the air to which mating cover 118 and surface 112 are exposed. In another embodiment, temperature sensor 106 may be placed directly behind mating cover 118 in order to position temperature sensor 106 as close as possible to the air to which mating cover 118 and surface 112 are exposed (i.e., as far as possible from the wall to which housing 102 is mounted), and to minimize the response time required for temperature sensor 106 to detect changes in temperature of the air to which mating cover 118 and surface 112 are exposed. In the illustrated embodiment, the temperatures sensed by temperature sensors 104 and 106 are sensed primarily by the conduction of these temperatures through housing 102. In another embodiment, housing 102 may also include openings or vents to permit the flow of air through housing 102, and temperature sensor 106 may be mounted within housing 102 such that it is spaced apart from temperature sensor 104 while being

exposed to the flow of air such that the temperature of the air flowing through housing 102 is sensed.

[0022] While the illustrated embodiment shows both sensors 104 and 106 mounted within housing 102, other mounting locations are possible. For example, in one embodiment, temperature sensor 106 may be mounted outside housing 102. In another embodiment, temperature sensing device 106 may be mounted on an extension to housing 102 to increase the distance between temperature sensor 104 and 106. In yet another embodiment, temperature sensors 104 and 106 may be mounted in separate housings, so long as they are both in communication with processor 108.

[0023] Processor 108 is coupled to temperature sensors 104 and 106 and may be any suitable processor. Processor 108 is configured to receive a temperature measurement from temperature sensor 104 and a temperature measurement from temperature sensor 106. In the illustrated embodiment, processor 108 is shown as being coupled to temperature sensors 104 and 106 and mounted within housing 102. FIG. 2A illustrates a block diagram of this configuration according to one exemplary embodiment. In this embodiment, temperature sensors 104 and 106 provide analog output signals to analog-to-digital (A/D) converters 220 and 222. A/D converter 220 is coupled to processor 108 and provides a digital version of the analog output signal from temperature sensor 104 to processor 108. A/D converter 222 is coupled to processor 108 and provides a digital version of the analog output signal from temperature sensor 106 to processor 108. In another embodiment, the outputs of temperature sensors 104 and 106 may be multiplexed such that a single A/D may be used. Processor 108 is mounted within housing 102 and is coupled to communication port 224 such that it may communicate digital data or information via digital bus 226 to a controller 228 or other external device or system, such as a climate control system. In another embodiment, temperature sensors 104 and 106 provide a digital output signal such that analog-to-digital (A/D) converters 220 and 222 are not necessary.

[0024] In another embodiment, processor 108 is coupled to temperature sensors 104 and 106, but is located external to housing 102. FIG. 2B illustrates a block diagram of this configuration according to one exemplary embodiment. In this embodiment,

temperature sensors 104 and 106 provide analog output signals to processor 108, which is externally located in, for example, controller 228 or other external device or system, such as a climate control system. A/D converter 220 is coupled to processor 108 and provides a digital version of the analog output signal received from temperature sensor 104 to processor 108. A/D converter 222 is coupled to processor 108 and provides a digital version of the analog output signal received from temperature sensor 106 to processor 108. In another embodiment, temperature sensors 104 and 106 provide a digital output signal such that analog-to-digital (A/D) converters 220 and 222 are not necessary.

[0025] Processor 108 is also configured to use the temperature measurements from temperature sensors 104 and 106 to estimate a third temperature. For example, in one embodiment processor 108 may be configured to estimate the temperature of an air mass in a room or other area in which temperature sensing device 100 is mounted using temperature measurements from temperature sensors 104 and 106. Because temperature sensing device 100 may be located on the boundary surface of the room air mass, neither temperature sensor 104 nor temperature sensor 106 may be sufficiently exposed to the actual temperature of the air mass. Additionally, temperature sensing device 100 may further be mounted to the surface of a structure, such as an exterior wall, such that it is exposed to various external or other temperature effects. Accordingly, in this embodiment processor 108 may be configured to estimate the third temperature from the temperature measurements from temperature sensors 104 and 106 by compensating for the various external temperature effects due to the mounting location of temperature sensing device 100.

[0026] The third temperature may be estimated from the temperature measurements from temperature sensors 104 and 106 in a number of ways. For example, in one embodiment, the third temperature is estimated using a predetermined extrapolation function which defines an approximate mathematical relationship between the temperature measurements from temperature sensors 104 and 106 and the third temperature to be estimated. In other embodiments, methods other than mathematical extrapolation may be used alternatively or in addition to the extrapolation function.

[0027] The extrapolation function may be a linear extrapolation function, or alternatively, a non-linear extrapolation function. The particular choice of either a linear or non-linear extrapolation function depends upon the particular application and/or location of temperature sensing device 100, as well as the desired level of accuracy. For example, the extrapolation function may be selected based on known or estimated environmental (e.g., airflows, etc.) or structural conditions (e.g., building materials, etc.) where temperature sensing device 100 is located. In one embodiment, where the air temperature distribution across a room in which temperature sensing device 100 is located is expected to be approximately linear based on known environmental or structural conditions (e.g., low airflow velocities through the room or area in which temperature sensing device 100 is mounted, or through temperature sensing device 100 itself), a first order linear extrapolation function of the form $y = mx + b$ may be used to estimate the third temperature, where y is the temperature to be estimated, m is a predetermined coefficient, x is the mathematical difference between the temperatures sensed by temperature sensors 104 and 106, and b is the temperature sensed by temperature sensor 104. In other embodiments, a non-linear extrapolation function or a more complex linear extrapolation function may be used to compensate for additional or more complex factors such as, for example, erratic airflows in the room or area in which temperature sensing device 100 is mounted, or through temperature sensing device 100 itself, or different materials in either temperature sensing device 100 or in the exterior structure of the building structure to which temperature sensing device 100 is mounted. In other embodiments, the extrapolation function may also include additional terms or variables to accommodate additional temperature sensors or other inputs depending on the desired accuracy.

[0028] Any number of extrapolation functions may be used to estimate the third temperature. For example, in one embodiment, temperature sensing device 100 may use a first linear extrapolation function where the temperature sensed by temperature sensor 104 is lower than the temperature sensed by temperature sensor 106, and a second linear extrapolation function where the temperature sensed by temperature sensor 104 is higher than the temperature sensor 106 to account for differing

thermodynamic conditions to which temperature sensing device 100 is exposed. In other embodiments, additional or fewer extrapolation functions may be used.

[0029] The extrapolation function may also include one or more predetermined coefficients which may function as correction factors. Each correction factor may be determined based on, for example, the shape, size, and temperature sensor locations of device 100, as well as the magnitude of known environmental or structural conditions such that the error of the temperature estimate from the extrapolation function is minimized. For example, in one embodiment using a first order linear extrapolation function of the form $y = mx + b$, the coefficient m may be a predetermined correction factor which compensates for the shape, size, and location of the temperature sensors of temperature sensing device 100, as well as one or more known or estimated environmental or structural conditions of a building or room in which temperature sensing device 100 is located, such as known or estimated air flow velocities, room dimensions, expected outdoor and indoor temperature ranges, building materials, etc. In another embodiment, the predetermined correction factor may be determined using computational fluid dynamic (CFD) simulations. CFD similations utilize the size, shape, and sensor locations of temperature sensing device 100, various estimated or known environmental and structural conditions, and various conservation of energy, mass and momentum equations in order to model, for example, the air mass in a room or area in which temperature sensing device 100 is located. For example, the CFD simulations may determine the contours of one or more temperature gradients due to external temperature effects in areas where temperature sensing device 100 may be located, which may then by used to determine each correction factor.

[0030] In this way, temperature sensing device 100 may compensate for errors due to external or other temperature effects such as a wall surface temperature that is significantly warmer or colder than the air temperature of the room or zone, or minimal airflow in the area where temperature sensing device 100 is located. Reduced errors in temperature measurements provide, for example, more accurate and efficient climate control system performance.

[0031] Temperature sensing device 100 may also be used to determine air temperature set points which improve the thermal comfort of an occupant in a room or

area in which temperature sensing device 100 is located. For example, in a typical setting, thermal comfort may be achieved when the occupant's skin temperature is in a range of approximately 91.0 degrees Fahrenheit to 93.0 degrees Fahrenheit. Skin temperature is related to the balance between body heat generated by the occupant and body heat transfers in the form of body heat losses or gains to the environment of the room or area.

[0032] The dominant body heat transfer mechanisms are convection and radiation. Convective body heat transfer rates are a function of room air velocity and room air temperature. In most cases the room air velocity is constrained within narrow limits by, for example, the HVAC system design, and the air temperature is measured using a temperature sensor such as a thermostat. Accordingly, air temperature set points that provide thermal comfort, in the absence of significant radiation heat transfer, may be identified over time.

[0033] However, if radiation heat transfer rates are high, then occupants will not be comfortable using these air temperature set points. Radiation heat transfer rates are a direct function of photon exchange rates between the occupant and the surfaces of the room or area that encloses the occupant. The primary driving force for photon emission is temperature, and thermal comfort problems may occur when external surfaces of the room or area are warmer or colder than normal. This can occur, for example, when an external surface of a ceiling or wall associated with the room or area is in contact with the outdoors. Temperature sensing device 100 may be accordingly configured to sense the temperature at or around the wall or ceiling, estimate the associated radiation heat transfer rates, and estimate an air temperature set point to compensate for the radiation effects. Thus, occupant comfort may be improved when radiation heat transfer rates are high.

[0034] FIG. 3 illustrates an embodiment of temperature sensing device 100 (shown in FIG. 1) wherein a temperature sensing device 300 is mounted to an exterior wall 350 of a building. Temperature sensing device 300 includes a housing 302, temperature sensors 304 and 306, and a processor 308. Housing 302 is shaped such that it has a surface 310 and a surface 312 spaced apart from surface 310. Surface 310 is configured to be adjacent to a surface 354 of exterior wall 350, to which housing

302 is mounted, and surface 312 is configured to be spaced apart from surface 354 of exterior wall 350 and exposed to an air temperature at a distance from surface 354. Temperature sensor 304 is mounted proximate to surface 310 of housing 302, and temperature sensor 306 is mounted proximate to surface 312 of housing 302. Temperature sensor 304 is configured to sense the temperature T_1 at or near surface 354 of exterior wall 350, to which housing 302 is mounted, and to which surface 310 is adjacent. Temperature sensor 306 in this embodiment is configured to sense the temperature T_2 of the air at a distance from surface 354. Temperature sensing device 300 is configured to estimate temperature T_{IA} of the air mass inside the room or area including exterior wall 350 using the temperature T_1 of surface 354 of exterior wall 350 sensed by temperature sensor 304, and temperature T_2 of the air at a distance from surface 354 sensed by temperature sensor 306.

[0035] In the illustrated embodiment, the temperature T_{OA} of the outside air is significantly lower than the temperature T_{IA} of the air inside a room or area including exterior wall 350. The external effect of the lower outside air temperature T_{OA} on the inside air temperature T_{IA} is manifested in the form of several temperature gradients. The temperature graph shown in FIG. 3 illustrates various temperature gradients that may be identified given several known or estimated environmental or structural conditions and using CFD simulations to model the air mass inside the room under these conditions. For example, a temperature gradient 360 may exist across the thickness of exterior wall 350 such that the temperature of wall 350 increases from exterior surface 352 to interior surface 354. A temperature gradient 362 may exist across temperature sensing device 300 between surface 310 and surface 312 of housing 302. A temperature gradient 364 may exist between surface 312 of housing 302 and a distance beyond surface 312 at which temperature T_{IA} is to be estimated. Accordingly, due to the location of temperature sensing device 300 within a different temperature gradient than T_{IA}, neither the temperature sensed by temperature sensor 304 nor the temperature sensed by temperature sensor 306 is the actual temperature of the inside air T_{IA}.

[0036] Temperature sensing device 300 is configured to estimate temperature T_{IA} from T_1 and T_2 using one of the following two linear extrapolation functions:

$$T_{IA} = T_1 + C_1(T_2 - T_1) \quad (1)$$

$$T_{IA} = T_1 + C_2(T_2 - T_1) \quad (2)$$

where C_1 and C_2 are predetermined correction factors. Eq. (1) is used by temperature sensing device 300 where T_1 is lower than T_2, and Eq. (2) is used by temperature sensing device 300 where T_1 is higher than T_2. In this embodiment, two linear extrapolation functions are used in order to account for differing thermodynamic conditions. Linear extrapolation functions may used as an approximation of the temperature distribution across the room from surface 354 to the location where T_{IA} is to be estimated based on, for example, low airflow velocities in the room or through temperature sensing device 300. Predetermined correction factors C_1 and C_2 may be determined using, for example, CFD simulations, including the temperature gradients shown in FIG. 3.

[0037] According to Eq. (1), where T_1 is lower than T_2, the difference between T_2 and T_1 is multiplied by correction factor C_1 to estimate the increase in temperature from surface 354 to the location where T_{IA} is to be estimated. This quantity is then added to T_1 to estimate T_{IA}. For example, in one embodiment, C_1 may be set at 1.24, T_1 may be measured to be 56 degrees Fahrenheit, and T_2 may be measured to be 67 degrees Fahrenheit. According to Eq. (1), T_{IA} is estimated to be 69.64 degrees Fahrenheit, which represents a 2.64 degree compensation of the temperature measured by temperature sensor 306. Similarly, according to Eq. (2), where T_1 is higher than T_2, the difference between T_2 and T_1 is multiplied by correction factor C_2 to estimate the decrease in temperature from surface 354 to the location where T_{IA} is to be estimated. This quantity is then added to T_1 to estimate T_{IA}. For example, in one embodiment, C_1 may be set at 1.45, T_1 may be measured to be 67 degrees Fahrenheit, and T_2 may be measured to be 56 degrees Fahrenheit. According to Eq. (2), T_{IA} is estimated to be 51.05 degrees Fahrenheit, which represents a 4.95 degree compensation of the temperature measured by temperature sensor 306.

[0038] It should be understood that the construction and arrangement of the elements of the temperature sensing device in the exemplary embodiments are illustrative only. Although only a few embodiments of the present invention have been described in detail in this disclosure, many modifications are possible without

materially departing from the novel teachings and advantages of the subject matter recited in the claims. For example, the temperature sensing device may be adapted for use in other systems or locations, may incorporate additional temperature sensors or other inputs, or may include other variables or factors in the extrapolation function. Accordingly, all such modifications are intended to be included within the scope of the present invention as defined in the appended claims. Unless specifically otherwise noted, the claims reciting a single particular element also encompass a plurality of such particular elements. The order or sequence of any process or method steps may be varied or re-sequenced according to alternative embodiments. In the claims, any means-plus-function clause is intended to cover the structures described herein as performing the recited function and not only structural equivalents but also equivalent structures. Other substitutions, modifications, changes and/or omissions may be made in the design, operating conditions and arrangement of the preferred and other exemplary embodiments without departing from the spirit of the present invention as expressed in the appended claims.